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The Araucaria Project: The distance to the Small Magellanic Cloud from near infrared photometry of Type II Cepheids[1]

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ABSTRACT

We have obtained deep near infrared J- and K-band observations of 14 BL Herculis and 5 W Virginis SMC stars from the OGLE III survey with the ESO New Technology Telescope equipped with the SOFI infrared camera. From these observations, period-luminosity (P-L) relations in the J and K_s 2MASS bands were derived. The slopes of the K and J band relations of -2.15 $\pm$ 0.19 and -1.95 $\pm$ 0.24, respectively, agree very well with the corresponding slopes derived previously for population II Cepheids in globular clusters, Galactic bulge and in the Large Magellanic Cloud. The distance modulus to the SMC obtained from our data using P-L relation derived for globular cluster Cepheids equals 18.85 ± 0.07 (statistical) ± 0.07 (systematic without including potential metallicity effect), which within the uncertainties agrees well with the results obtained with other methods.

Key words: *Stars: Variables: W Virginis, BL Herculis, Galaxies: Distances and Redshifts, Galaxies: Individual: SMC, Galaxies: Stellar Content*

1. Introduction

The main goal of the long term program called the Araucaria project is to improve the calibration of the cosmic distance scale using extensive and high quality photometric and spectroscopic observations of several distance indicators in nearby galaxies (Pietrzynski and Gieren 2009, Gieren et al. 2005). Comparative analysis of high quality optical and near-infrared photometry of major distance indicators like Cepheids, RR Lyrae stars, red clump stars and tip of the red giant branch

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(TRGB) magnitude, in nearby galaxies possesing very different environments provide an opportunity to provide strong constraints on the population effects on these methods and construct a uniform set of accurate distances to the studied galaxies. Our results should also allow for a better calibration of other techniques of distance determinations like Type II Cepheids, blue supergiants, Anomalous Cepheids etc.

Type II Cepheids are low-mass stars belonging to the disc and halo populations. They have periods and amplitudes in a similar range as classical Cepheids, but are about 1.5 - 2 mag fainter. We can divide them into four different subgroups. Three of them: BL Herculis stars, W Virginis stars and RV Tauri stars show very similar period-luminosity relations and the usual criterion of the division between them is the period. We adopted as in Soszyński et al. (2010), 4 and 20 days as the period limits to distinguish these stars. The fourth group, peculiar W Virginis stars, have light curves different from the typical light curves of W Vir stars and are a little brighter (Soszyński et al. 2008).

Recent application of Type II Cepheids for distance determination to the Galactic Center (Kubiak and Udalski, 2003; Groenewegen, Udalski and Bono, 2008), and the LMC (Matsunaga et al. 2009, hereafter M09) confirmed that these stars are very promising distance indicators. Therefore, an accurate calibration of their P-L relations, especially in the near infrared domain, where the extinction is very small, is of great importance.

In this paper we will present the J and K_s band period-luminosity relations based on 19 stars taken from the OGLE III catalogue of type II Cepheids in the SMC (Soszyński et al. 2010), compare it with similar relations for objects in the LMC (M09), Galactic bulge (Groenewegen, Udalski and Bono, 2008) and in globular clusters (Matsunaga et al. 2006, hereafter M06), and use it to calculate the SMC distance.

2. Observations

We chose 14 BL Her and 5 W Vir stars from the OGLE III catalogue (Soszynski et al. 2010) and observed them during three Araucaria observing runs, using the SOFI IR camera attached to the ESO New Technology Telescope (NTT) at La Silla Observatory. The wide-field mode was used to yield a 4.5 $\times$ 4.5 arcmin field of view and a scale of 0.288 arcsec per pixel. In order to account for frequent sky-level variations in the near IR passbands a dithering technique was imployed. The detector readout time was adjusted to keep ADUs below 10000 (e.g. well within linearity regime of the detector) during the observations. The whole sequence of dithered observations (typically 15-21 different positions) for a given field resulted in a total net integration time of 21 minutes in the K_s-band (15 minutes for stars with period longer than 16 days) and 5.5 minutes in J_s, and allowed us to obtain a very good signal to noise ratio of better than 50 for our target stars.

Detailed information about each observed field and observation conditions dur-

ing the exposures is given in Table 1. (Note that name of each field is the name of the OGLE star, on which this field is centered).

Table 1

Observational information on the target fields

Field name	R.A. 2000	Decl. 2000	Date of observation	HJD-2450000 of J_s exposure	HJD-2450000 of K_s exposure	Conditions	Extinction $E(B-V)$
OGLE-SMC-T2CEP-02	00:34:53.51	-72:58:45.9	2010 Dec 02	5168.707950	5168.719090	STD	0.087
OGLE-SMC-T2CEP-03	00:37:08.35	-73:43:04.9	2010 Dec 02	5168.730445	5168.741590	STD	0.070
OGLE-SMC-T2CEP-04	00:38:20.36	-73:17:16.4	2010 Dec 04	5170.618600	5170.689680	STD	0.070
OGLE-SMC-T2CEP-05	00:42:03.81	-74:01:24.6	2010 Dec 02	5168.666730	5168.677870	STD	0.087
OGLE-SMC-T2CEP-06	00:42:16.01	-73:39:13.5	2010 Dec 03	5169.554910	5169.566020	STD	0.078
OGLE-SMC-T2CEP-08	00:44:00.77	-73:22:54.4	2010 Dec 04	5170.592745	5170.603870	STD	0.089
OGLE-SMC-T2CEP-09	00:44:12.37	-72:59:28.5	2010 Dec 27	5193.702160	5193.690865	CLR	0.089
OGLE-SMC-T2CEP-15	00:49:36.92	-73:10:01.4	2010 Nov 05	5141.677870	5141.666550	STD	0.101
OGLE-SMC-T2CEP-16	00:50:12.58	-72:43:12.4	2010 Dec 28	5194.648940	5194.637630	CLR	0.101
OGLE-SMC-T2CEP-17	00:50:42.03	-71:39:18.4	2010 Dec 03	5169.676400	5169.687520	STD	0.087
OGLE-SMC-T2CEP-22	00:54:46.72	-73:48:32.6	2010 Dec 03	5169.740075	5169.751170	STD	0.087
OGLE-SMC-T2CEP-27	00:57:28.64	-73:31:26.9	2010 Dec 03	5169.700485	5169.711610	STD	0.087
OGLE-SMC-T2CEP-30	00:57:40.76	-73:03:04.9	2010 Nov 06	5142.690225	5142.678905	CLR	0.100
OGLE-SMC-T2CEP-33	00:59:03.09	-72:28:32.2	2010 Nov 06	5142.655995	5142.644685	CLR	0.100
OGLE-SMC-T2CEP-35	01:00:35.01	-73:46:57.9	2010 Nov 07	5143.576060	5143.567220	CLR	0.087
OGLE-SMC-T2CEP-37	01:03:46.50	-74:07:28.8	2010 Nov 07	5143.682545	5143.671235	CLR	0.087
			2010 Dec 26	5192.683115	5192.671810	STD	
OGLE-SMC-T2CEP-39	01:06:40.91	-73:07:05.0	2010 Nov 07	5143.606935	5143.596055	CLR	0.084
			2010 Dec 26	5192.629215	5192.617915	STD	
OGLE-SMC-T2CEP-40	01:08:46.85	-71:51:09.4	2010 Nov 07	5143.754020	5143.745155	CLR	0.087
			2010 Dec 27	5193.654555	5193.645705	CLR	
OGLE-SMC-T2CEP-42	01:23:26.69	-72:00:24.3	2010 Dec 27	5193.677110	5193.665815	CLR	0.087

Note: Extinction values are taken from the reddening maps of Udalski et al. (1999). For objects located outside the OGLE II fields we adopted mean value of $E(B-V)$ from all OGLE II fields (0.087 mag). The entries STD and CLR mean photometric and clear observing conditions, respectively.

3. Data reductions and calibrations

For all reductions and calibrations the pipeline developed in the course of Araucaria Project was used. First, we applied a two-step sky level subtraction process, including masking of stars with the IRAF[2] xdimsum package (Pietrzyński and Gieren 2002). Next, each single image was flat-fielded and stacked into the final deep field. Then point-spread function (PSF) photometry, including aper-

[2]IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the NSF.

ture corrections, was performed in the same way as described in Pietrzyński et al. (2002).

The data collected under photometric conditions were calibrated onto the standard UKIRT system using observations of 16 standard stars from the list published by Hawarden et al. (2001). The standard stars were observed at different air masses and hour angles spread in between the regular target fields acquisition. The accuracy of the zero points for both K and J band were estimated to be better than 0.02 mag. Next, the calibrated photometry was transformed onto the 2MASS photometric system using relations (37) and (39) given by Carpenter (2001). In order to perform an external check on the accuracy of the zero point of our photometry in each field we identified stars common to the 2MASS Point Source Catalog (Wachter et al. 2003). In each case the zero point offset in both J and K bands was always smaller than 0.02 mag. The photometry of fields observed under non-photometric conditions, were tied directly onto the 2MASS system comparing our instrumental j_s, k_s magnitudes with the 2MASS data.

Since most of our stars have just single epoch measurements we derived their mean magnitudes applying a simple method, following M09. Shortly, assuming that Type II Cepheids have similar light curve shapes in I and near infrared K and J bands, and using I-band light curves from (Soszyński et al. 2010) a correction between the observed random-phase K band magnitude and the mean magnitude can be derived. Mean magnitudes obtained in this way will be called phase-corrected data.

The calibrated data for all stars are presented in Table 2. In the columns are star name (from OGLE III catalogue), star type, period, K_s magnitude and $J-K_s$ color (at the phase of measurement), and mean K_s magnitude and $J-K_s$ color. All errors are uncertainties as returned by DAOPHOT.

4. Period-luminosity relations

A fundamental issue while applying P-L relations of pulsating stars for distance measurement is to reassure the use of the correct fiducial period-luminosity relation. M06 calibrated such a relation for Type II Cepheids using 46 stars (3 with periods longer than 20 days and only 7 with shorter than 4 days) from 26 globular clusters and in the K_s and J bands obtained

$$M_{K_s} = -2.41(\pm 0.05)\log P - 1.108(\pm 0.02) \tag{1}$$

$$M_J = -2.23(\pm 0.05)\log P - 0.864(\pm 0.03) \tag{2}$$

with standard deviations of 0.14 and 0.16 mag, respectively. In this paragraph we will check whether the P-L relations of Matsunaga can be applied to the SMC Type II Cepheids by computing the free least square fits for different subsamples of the observed target stars for both filters and comparing the resulting slopes with the slope from equations (1) and (2).

T a b l e 2

Calibrated magnitudes and colors for SMC population-II Cepheids

Star ID (OGLE)	Type	Period (days)	K_s (mag)	$J-K_s$ (mag)	$<K_s>$ (mag)	$<J-K_s>$ (mag)
OGLE-SMC-T2CEP-02	BL Her	1.3721870	17.54 ± 0.05	0.41 ± 0.06	17.39 ± 0.06	0.40 ± 0.08
OGLE-SMC-T2CEP-03	W Vir	4.3598789	16.75 ± 0.03	0.50 ± 0.04	16.50 ± 0.04	0.54 ± 0.05
OGLE-SMC-T2CEP-04	W Vir	6.5333997	15.54 ± 0.03	0.19 ± 0.04	15.58 ± 0.03	0.16 ± 0.04
OGLE-SMC-T2CEP-05	W Vir	8.2058890	15.92 ± 0.02	0.55 ± 0.03	15.83 ± 0.02	0.57 ± 0.03
OGLE-SMC-T2CEP-06	BL Her	1.2356136	17.71 ± 0.06	0.42 ± 0.07	17.67 ± 0.07	0.41 ± 0.09
OGLE-SMC-T2CEP-08	BL Her	1.4897859	16.97 ± 0.04	0.26 ± 0.04	16.90 ± 0.04	0.27 ± 0.05
OGLE-SMC-T2CEP-09	BL Her	2.9710719	16.83 ± 0.04	0.44 ± 0.04	16.85 ± 0.04	0.47 ± 0.04
OGLE-SMC-T2CEP-15	BL Her	2.5695964	16.25 ± 0.02	0.11 ± 0.03	16.32 ± 0.02	0.11 ± 0.03
OGLE-SMC-T2CEP-16	BL Her	2.1131980	16.91 ± 0.04	0.37 ± 0.04	17.01 ± 0.04	0.39 ± 0.05
OGLE-SMC-T2CEP-17	BL Her	1.2993097	17.29 ± 0.05	0.29 ± 0.06	17.16 ± 0.06	0.31 ± 0.07
OGLE-SMC-T2CEP-22	BL Her	1.4705261	17.69 ± 0.06	0.29 ± 0.07	17.75 ± 0.07	0.29 ± 0.09
OGLE-SMC-T2CEP-27	BL Her	1.5417249	17.60 ± 0.06	0.27 ± 0.07	17.66 ± 0.06	0.21 ± 0.08
OGLE-SMC-T2CEP-30	BL Her	3.3889388	16.12 ± 0.04	0.52 ± 0.05	16.00 ± 0.04	0.52 ± 0.05
OGLE-SMC-T2CEP-33	BL Her	1.8776865	16.63 ± 0.03	0.38 ± 0.03	16.72 ± 0.03	0.31 ± 0.04
OGLE-SMC-T2CEP-35	W Vir	17.1814841	15.07 ± 0.01	0.36 ± 0.01	15.21 ± 0.01	0.36 ± 0.02
OGLE-SMC-T2CEP-37	BL Her	1.5590709	17.29 ± 0.03[1]	0.25 ± 0.04[1]	17.18 ± 0.03	0.35 ± 0.04
			17.06 ± 0.03[2]	0.43 ± 0.05[2]		
OGLE-SMC-T2CEP-39	BL Her	1.8875529	16.95 ± 0.03[1]	0.29 ± 0.04[1]	16.90 ± 0.03	0.33 ± 0.04
			16.92 ± 0.03[2]	0.38 ± 0.05[2]		
OGLE-SMC-T2CEP-40	W Vir	16.1110373	15.27 ± 0.01[1]	0.53 ± 0.01[1]	14.93 ± 0.01	0.50 ± 0.01
			15.41 ± 0.01[3]	0.48 ± 0.02[3]		
OGLE-SMC-T2CEP-42	BL Her	1.4874289	17.29 ± 0.04	0.46 ± 0.04	17.31 ± 0.04	0.50 ± 0.06

[1] night 07-12-2009, [2] night 26-12-2009, [3] night 27-12-2009

In order to produce reddening corrected P-L relations for the SMC Type II Cepheids we adopted the E(B-V) values for all observed fields from the OGLE reddening maps (Udalski et al. 1999) as listed in Table 1, and assume the reddening law of Cardelli et al. (1989) (e.g. $R_V = 3.1$, $A_{K_s} = 0.365 \times E(B-V)$, $A_J = 0.866 \times E(B-V)$) In the case of stars with two measurements we took mean value of them. Figures 1,2,3 and 4 show the results for a mixed sample of BL Her and W Vir stars, and BL Her stars solely, respectively (unfortunately, we have not enough data to obtain a credible relation for W Vir stars alone). In all figures circled points and solid line represent the phase-corrected data, whereas crosses and dashed lines are for uncorrected observations.

Last square solutions for BL Her and W Vir data yield:

$$K_s = -2.15(\pm0.19)\log P + 17.59(\pm0.11), (\sigma = 0.29)$$
$$J = -2.05(\pm0.23)\log P + 17.87(\pm0.13), (\sigma = 0.34)$$

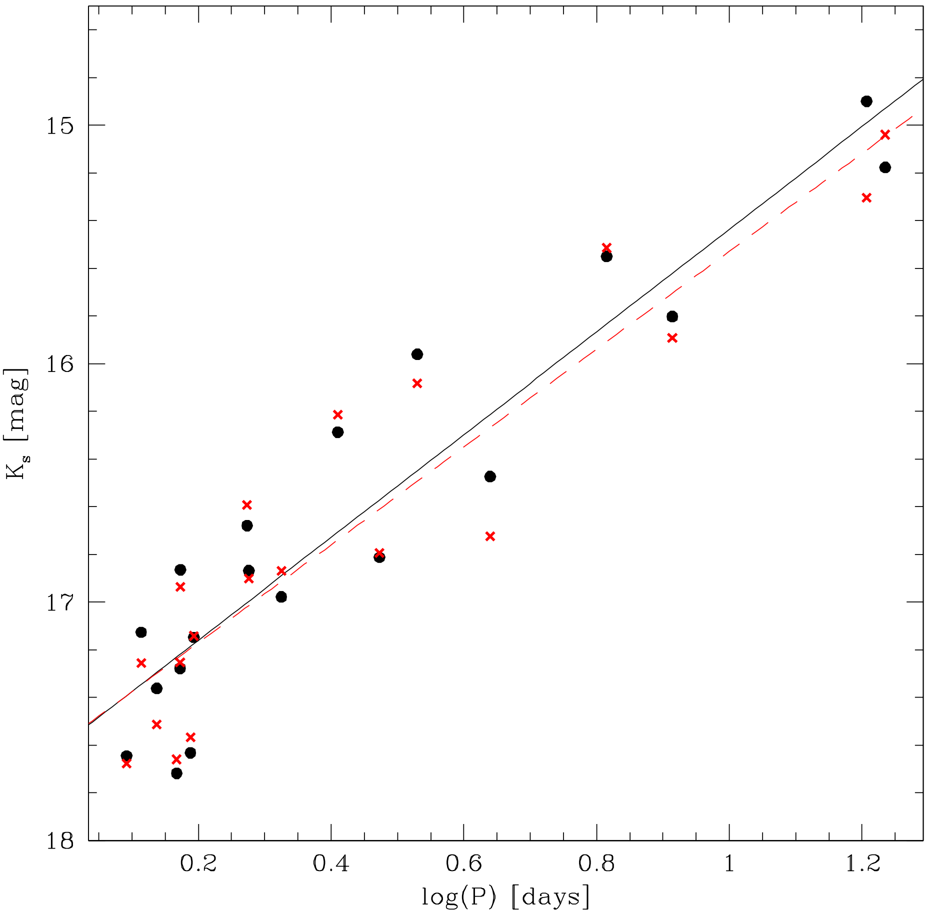

Fig. 1. Reddening free K_s band P-L relation of type II Cepheids in the SMC. Filled circles and solid line represent phase-corrected data, while crosses and dashed line stand for uncorrected observations.

in the case of phase-corrected data and

$$K_s = -2.05(\pm 0.20)\log P + 17.58(\pm 0.11), (\sigma = 0.30)$$
$$J = -1.95(\pm 0.24)\log P + 17.86(\pm 0.13), (\sigma = 0.36) \quad (3)$$

for uncorrected data.

For BL Her data solely we obtained:

$$K_s = -3.04(\pm 0.61)\log P + 17.79(\pm 0.17), (\sigma = 0.28)$$
$$J = -2.91(\pm 0.69)\log P + 18.06(\pm 0.19), (\sigma = 0.33)$$

in the case of phase-corrected data and

$$K_s = -3.14(\pm 0.56)\log P + 17.82(\pm 0.16), (\sigma = 0.26)$$
$$J = -3.02(\pm 0.66)\log P + 18.09(\pm 0.19), (\sigma = 0.31)$$

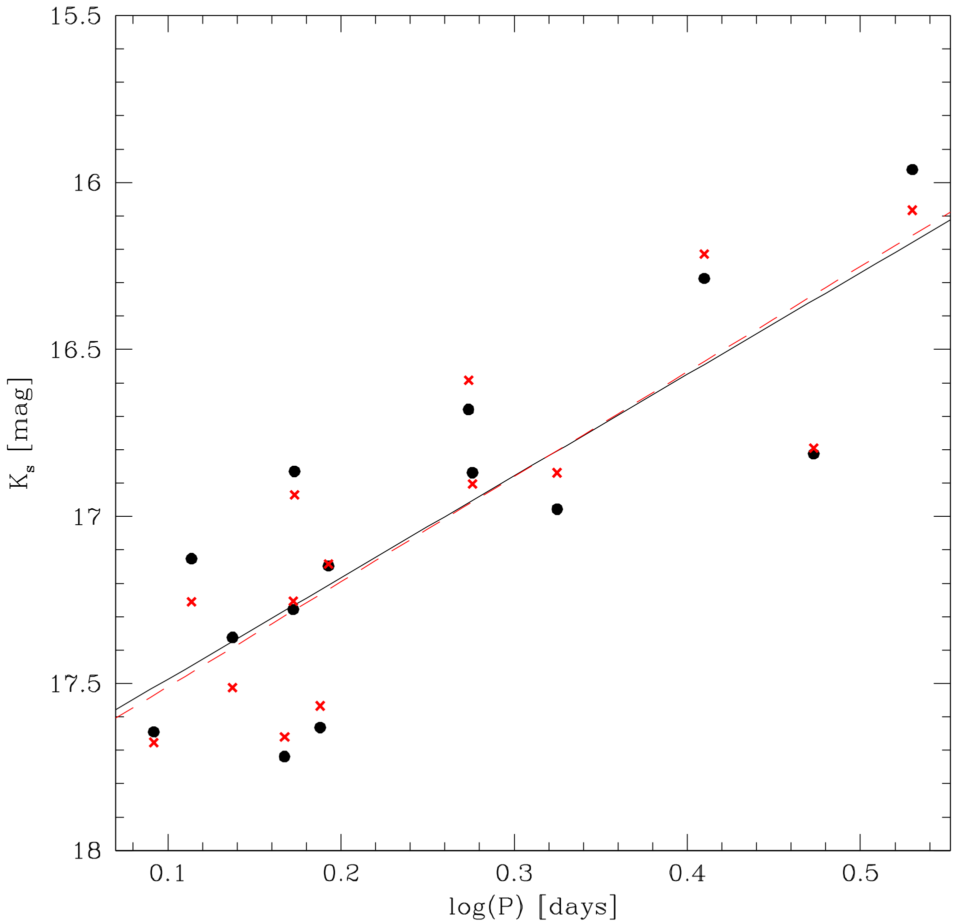

Fig. 2. Reddening free K_s band P-L relation of BL Her stars in SMC. Filled circles and solid line represent phase-corrected data, crosses and dashed line stand for uncorrected observations

for uncorrected data.

As is clearly visible, the phase-correction method did not allow to reduce the scatter on the observed J and K-band P-L relations. A method for correction of mean magnitudes should take into account different shapes of the Type II Cepheids light curves and the phase shift bewteen the maximum in the optical and near infrared bands. Such a technique has been developed for Classical Cepheids by Soszynski et al. (2005). Unfortunately, template light curves in the near infrared bands are still lacking for Type II Cepheids, so in the following we decided to use the uncorrected, random-phase data.

The scatter on the relations is significantly larger in comparison with the results obtained for Type II Cepheids in the LMC, the Galactic bulge and Galactic globular clusters (M09, M06, Groenewegen,Udalski and Bono, 2009). This fact is mostly related to the geometrical extension of the SMC in the line of sight, and also to using single-phase data to construct the P-L relation. This, together with the relatively

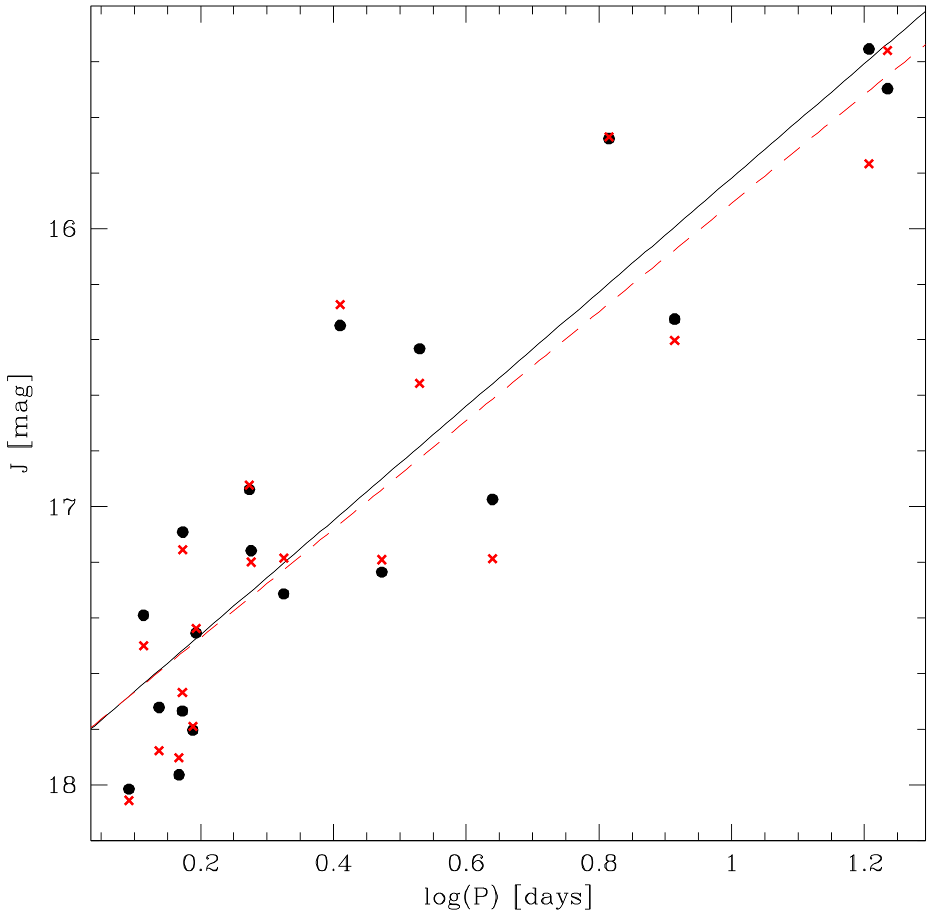

Fig. 3. Reddening free J band P-L relation of type II Cepheids in the SMC. Filled circles and solid line represent phase-corrected data, while crosses and dashed line stand for uncorrected observations.

small range of periods of BL Her stars and the small number of W Virginis stars in our sample, prevented us from providing a strong test wether the J and K-band P-L relations of these stars and W Vir are co-linear in the SMC. Since within the uncertainties (2 σ) the is no evidence for a difference in the slopes derived for the combined set of Type II Cepheids and BL Her stars alone, and M09 have shown that the relations for BL Her and W Vir stars are co-linear in the LMC, we decided to use the combined sample for the distance determination to the SMC.

5. Distance determination

The slopes of our J and K_s-band P-L relations obtained for the SMC Population II Cepheids (K_s: -2.05 $\pm$ 0.20, J: -1.95 $\pm$ 0.24) agree within their uncertainties with the corresponding slopes obtained for these stars in the LMC (M09; K_s: -2.278 $\pm$ 0.047, J: -2.163 $\pm$ 0.044), Galactic bulge (Groenewegen, Udalski and Bono, 2009; K_s: -2.24 $\pm$ 0.14), globular clusters (M06; K_s: -2.41 $\pm$ 0.05, J: 2.23

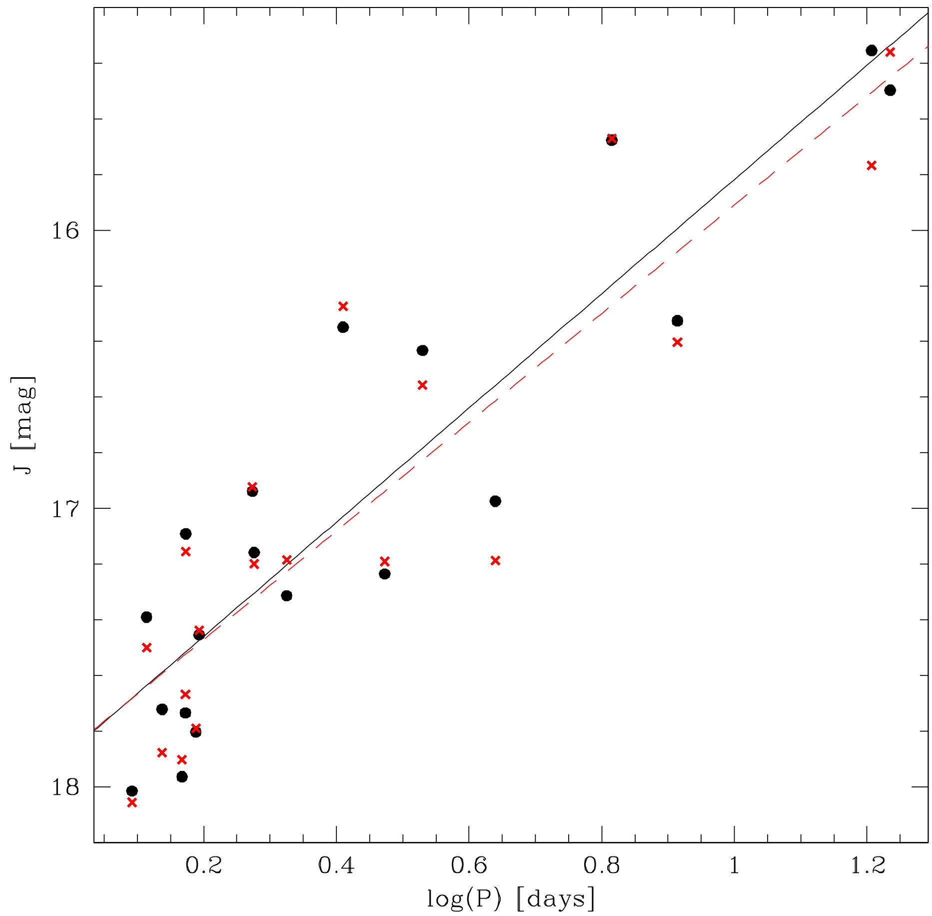

Fig. 4. Reddening free J band P-L relation of BL Her stars in SMC. Filled circles and solid line represent phase-corrected data, crosses and dashed line stand for uncorrected observations.

$\pm$ 0.05), and with the theoretical slopes (Di Criscienzo et al. 2007; K_s: -2.38 $\pm$ 0.02, J: -2.29 $\pm$ 0.04).

Therefore, we used the calibrations of M06 as a fiducial P-L relations to calculate distance to the SMC based on our data. The least square fitting gives the following SMC distance moduli:

$$(m-M)_0 = 18.85 \pm 0.07(\text{statistical}) \ (K_s \text{ band}) \tag{4}$$

$$(m-M)_0 = 18.85 \pm 0.09(\text{statistical}) \ (J \text{ band}) \tag{5}$$

These results are (by coincidence) identical to each other and to the distance modulus of 18.85 ± 0.11 derived from OGLE optical photometry of Type II Cepheids (Majaess et al. 2009). Within its uncertainties they also agree with the SMC distance moduli obtained from near-infrared photometry of RR Lyr variables (Szewczyk et al. 2009) and red clump stars (Pietrzyński al. 2003). Moreover the differencial distances Galactic bulge - LMC - SMC calculated from the K band photometry of

Type II Cepheids agree very well with the corresponding data obtained for other distance indicators (Cepheids, TRGB, RR Lyrae, etc; e.g. Udalski 2000, Groenewegen, Udalski, Bono 2009). Our results suggest that any population dependence of the slope and zero point of the K_s and J band P-L relations for Type II Cepheids should be small. In line with this conclusion, M06 found also no evidence for significant population effects on JHK band P-L relatios of Type II Cepheids from the globular cluster data they used. These conclusions are further supported by theoretical models (Bono, Caputo & Santolamazza, 1997, Di Criscienzo et al. 2007), which suggest that the properties of Type II Cepheids should be only minimally affected by metallicity.

In order to estimate the systematic error on the SMC distance determined in this paper we took into account the errors associated with photometric zero points (0.02 for both filters), transformation onto the 2MASS system (0.01), reddening (0.01 for K_s and 0.02 for J band) and the adopted fiducial P-L relation of M06. M06 combined the sample of Type II Cepheids observed in different clusters using distance moduli calculated based on the magnitudes of the horizontal branches of the clusters. They adopted the relation of Gratton (2003) (M_V=0.22[Fe/H]+0.89), calibrated based on the main sequence distances. Therefore it is rather difficult to estimate a realistic systematic error of the zero point of the M06 calibration. Independently, the zero point of the P-L relation for Type II Cepheids may be calibrated using two Galactic stars with pulsational parallaxes (Feast et al. 2008) with a precision of 0.06 mag. If we adopt both zero point calibrations and calculate a distance to the LMC the difference in the corresponding distance moduli is 0.04 mag only. Therefore it is reasonable to assume 0.06 as a realistic error of the zero point of the current calibrations of the P-L relation of Type II Cepheids. Combining all errors quadratically we obtain 0.07 mag as the total systematic error of the SMC distance. This error does not contain the possible effect of a metallicty dependence on the slope and zero point of the Type II Cepheids P-L relation. However, as has been discussed above such an effect is supposed to be small.

6. Summary and conclusions

We presented precision J- and K_s-band photometry of 19 Type II Cepheids in the SMC. The slope of the resulting J and K_s band P-L relations were found to be, within the errors, in good agreement with the corresponding slopes obtained for Type II Cepheids in the LMC (M09), Galactic bulge (Groenewegen, Udalski and Bono) and globular clusters (M06).

Assuming the fiducial P-L relation of M06 the following SMC distance modulus was derived from our data:

$$(m-M)_0 = 18.85 \pm 0.07(\text{statistical}) \pm 0.07(\text{systematic}) \tag{6}$$

This result agrees very well with recent distance determinations to the SMC

based on other techniques. Moreover, the differencial distances between the LMC, SMC and Galactic Bulge derived from Type II Cepheids are very similar to those obtained from Cepheids, TRGB, RR Lyrae stars and red clump stars, which suggests that the population effects on the slope and/or zero point of the Type II Cepheid P-L relation must be small. Our results confirm that Type II Cepheids (W Vir and BL Her) are very good standard candles.

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